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Co-utilization of biomass and natural gas in combined cycles through primary steam reforming of the natural gas

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Abstract

Power production from biomass can occur through external combustion (e.g. steam cycles, organic Rankine cycles, Stirling engines), or internal combustion after gasification or pyrolysis (e.g. gas engines, IGCC). External combustion has the disadvantage of delivering limited conversion efficiencies (max 30–35%). Internal combustion has the potential of high efficiencies, but it always needs a severe and mostly problematic gas cleaning.

The present article proposes an alternative route where advantages of external firing are combined with the potential high efficiency of combined cycles through co-utilization of natural gas and biomass. Biomass is burned to provide heat for partial reforming of the natural gas feed. In this way, biomass energy is converted into chemical energy contained in the produced syngas. Waste heats from the reformer and from the biomass combustor are recovered through a waste heat recovery system. It is shown that in this way biomass can replace up to 5% of the energy in the natural gas feed. It is also shown that in the case of combined cycles, this alternative route allows for external firing of biomass without important drop in cycle efficiency.

Keywords: Biomass; Methane–steam reforming; Combined cycle; High efficiency

1. Introduction

The system proposed in the present paper combines the advantages of external combustion (no gas cleaning) with the advantages of internal combustion (higher efficiencies). This is realised by using the heat from the external combustion of biomass for partial primary reforming of natural gas into mainly hydrogen and carbon monoxide (see Fig. 1). In this way, the biomass energy is transferred into the syngas as chemical energy and the biomass exhaust gases are kept separate from the syngas and the internal parts of the gas turbine.

The principles of combining the external biomass firing with a gas turbine cycle are further detailed in Fig. 2, as follows:

- Biomass (1) is burnt in a furnace (3).
- The reforming reaction takes place in the tubes surrounding the furnace and containing the catalyst (7). The combustion air (2) needs to be preheated up to at least 600 °C and the amount must yield $\pm 6\%$ O_2 in the exhaust gases (4). Preheating will occur in a designated heat exchanger network (HEN).
- The exhaust gases (4) with a temperature of 700 °C, will feed the HEN.
- Natural gas, after desulphurization, is mixed with steam (6) and preheated to $\pm 650\,^{\circ}C$ before entering the reformer (7). The required heat for natural gas and steam will be drawn from the HEN.
- Heat from the biomass furnace (3) feeds the reformer reactions (7):

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H^0{}_{298} = 206\,\mathrm{kJ/mol} \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0{}_{298} = -41\,\mathrm{kJ/mol} \tag{2}$$

- Biomass energy is in this way partially converted into chemical energy in the syngas (10).

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Nomenclature

LHV	lower heating value (J/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{W}$	net power output (W)
η	LHV efficiency
BBHRS	black box heat recovery system
HEN	heat exchanger network
CC	steam and gas turbine combined cycles

- To avoid coking in the reformer, a sufficient excess of steam is added. If appropriate, excess water is condensed and recycled (8) after the reformer.
- The obtained syngas (10) is cooled to a temperature specified by the gas turbine supplier (<300 °C). The heat will be used in the HEN (9).
- The heat of the exhaust gases is recuperated in the HEN (11). This recuperation consists of the (existing) bottom cycle feed and a surplus to close the cycle energy balance.

It is to be observed that the combustion in preheated air of 600 °C can induce thermal NO_x during the biomass combustion, which can be compensated by the lower oxygen levels present in the gas turbine exhaust. It is anyway difficult to estimate the NO_x levels at this stage of the work.

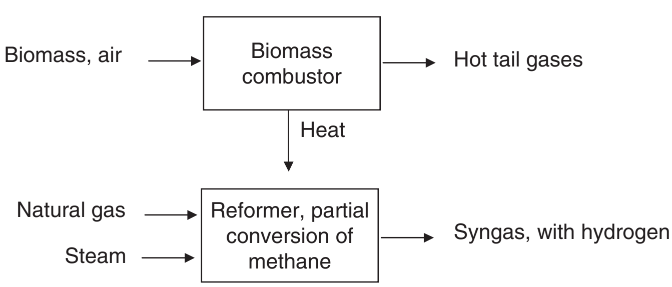

Fig. 1. Concept of steam reforming based on external combustion of biomass.

2. Previous work

The idea of using methane–steam reforming in gas turbine cycles is not new. Two relevant papers describing the use of methane–steam reforming for heat recovery purposes are Adelman et al. [1] and more recently Fiaschi et al. [2]. Such 'chemically recuperated cycles' use a methane–steam reformer in order to extract heat from the full gas turbine exhaust stream, and transform this heat into chemical energy in the syngas [1]. Temperatures in the gas turbine exhausts are however too low to achieve a high amount of reforming, and the obtained energy recovery is therefore too limited for practical application. Fiaschi et al. [2] propose to overcome this problem by adding post-combustion of natural gas in the full exhaust of the gas turbine. They use the reforming not for purposes of heat recovery, but to capture CO_2 from the fuel feed prior to the combustion process. Another application of reforming is patented by Mittricker [3]. In this patent a reforming process is proposed to enrich fuels with low methane concentration with hydrogen. The syngas is dried in order to deliver a syngas suitable for use in gas turbines. The process integration is not further detailed. A patent was taken by Edelmann [4] in 1998 where it is proposed to feed the reforming by heat from coal combustion. According to

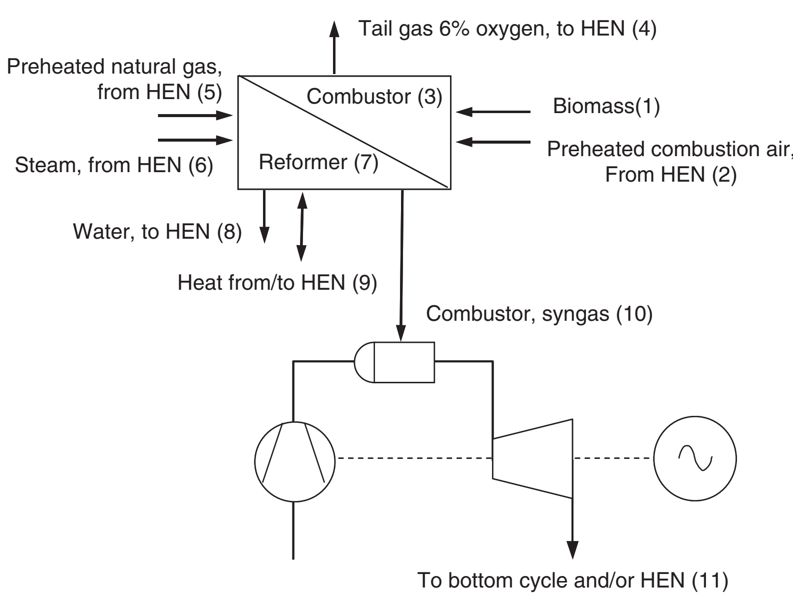

Fig. 2. Overall concept of the replacement of some natural gas by biomass through reforming (HEN = heat exchanger network).

this patent heat is taken from the coal combustion prior to steam production in a conventional steam cycle, whereas the syngas is used in a separate gas turbine plant. This procedure has been re-utilized recently by Han et al [5] with this time application to a combined cycle plant, but with limited process integration.

3. Application to combined steam and gas turbine cycles

In the following it is shown that in the case of steam and gas combined cycles (CC) the cycle efficiency can remain unaffected when replacing a limited amount of natural gas by biomass through the proposed reforming. This proof is based on a ‘black box’ approach developed by the authors and applied successfully in the past [6–8]. The black box approach occurs in four steps as follows:

In a *first step* an adiabatic control volume is chosen around all the reference CC components, with exclusion of the compressor, the expander and the steam turbine(s) (Fig. 3). The corresponding boundary conditions are given in Table 1. A certain amount of water is evaporated and preheated in the black box before being fed to the external steam turbines. This amount is calculated from the adiabatic condition of the black box. The amount of fuel flow is adjusted to reach 1200 °C at turbine inlet (turbine inlet temperature or TIT). Once the boundary conditions of the system are determined, the performance of the cycle is independent of what happens inside this ‘black box heat recovery system’ or BBHRS (principles of the first and second law of thermodynamics).

During the *second step*, the minimal amount of physical connections is made inside the BBHRS, and each connection between inlet and outlet is equipped with the necessary heaters and/or coolers. Fig. 4 is drawn for the reference CC case. The water is preheated, evaporated and superheated to 350 °C before feeding it to the external steam turbine(s) (1). Methane is injected into the combustion chamber with a temperature of 150 °C (2). The sole available heat source is the stack (3). Fuel and compressed air are injected in the combustor (4) where 1200 °C is imposed as exit temperature.

In the third step, ‘composite curves’ of the BBHRS are drawn (Fig. 5). Composite curves show at which temperatures heat is exchanged between components that require heat (cold curve), and components that provide heat (hot curve). Crossing hot and cold curves correspond to a violation of the second law of thermodynamics. From Fig. 5 it appears that the chosen boundary conditions do not lead to a second law violation. Boundary conditions can be adjusted to meet the optimal pinch point in the composite curves.

Table 1
Boundary conditions for the HEN, reference case and base 5% energy from biomass case

		Reference case	5% energy from biomass
Methane in	kg/s	0.017308	0.017607
	°C	20	20
	atm	20	20
Water in	kg/s	0.1323	0.1325
	°C	20	20
	atm	20	20
Gas turbine in	°C	1200	1200
	atm	19	19
Gas turbine out	°C	490	490
	atm	1	1
Steam turbine in	kg/s	0.1323	0.1164
	°C	350	350
	atm	20	20
Steam turbine out	°C	89	89
	atm	0.6	0.6
Stack out	kg/s	1.0173	1.0336
	°C	100	100
	atm	1	1

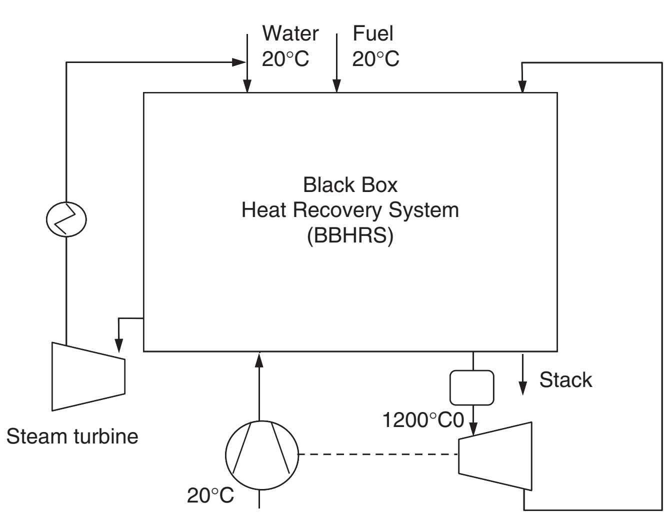

Fig. 3. Black box heat recovery system (BBHRS).

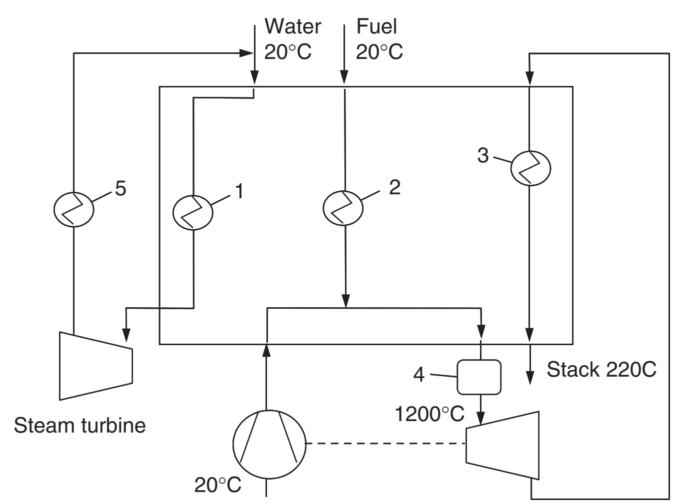

Fig. 4. BBHRS with minimal amount of connections.

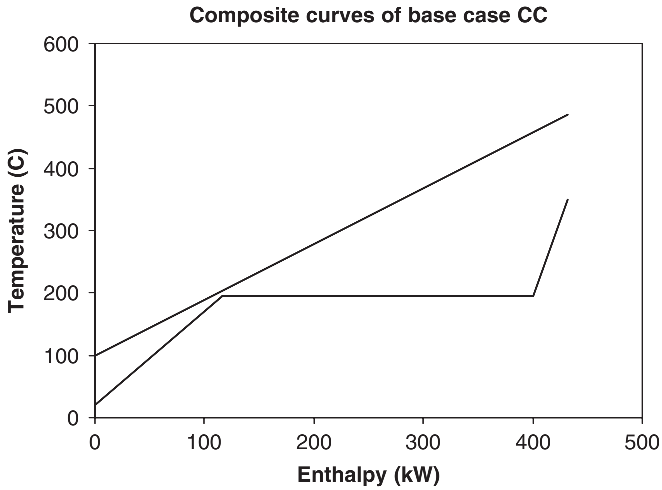

Fig. 5. Composite curves of the 'original' combined cycle.

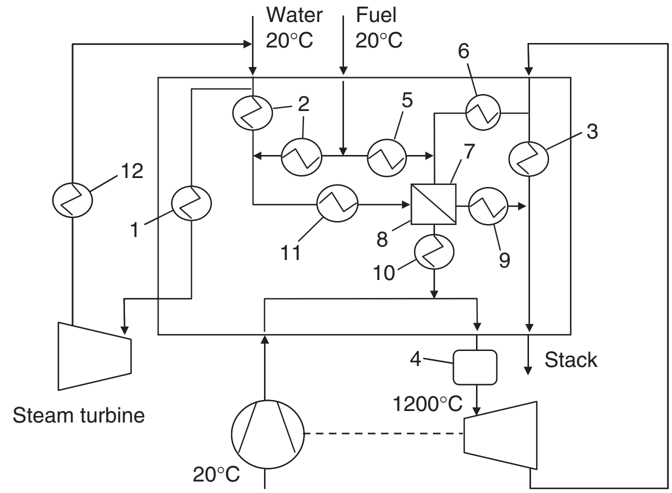

Fig. 6. Minimal connections when introducing biomass through reforming.

Eventually the BBHRS synthesis can be designed in the last step by means of a pinch analysis, as will be shown in Fig. 9.

4. Base case with reforming

The second to fourth steps can be repeated assuming a reforming reactor. The resulting cycle will be referred to as the 'adapted' cycle with 5% biomass energy input. Fig. 6 shows the minimum physical connections to be made to achieve the proposed reforming step. Components 1–4 are as before. The fuel and part of the water are preheated (2,11) and mixed in an isothermic way. The amount of water is determined by the desired steam–methane ratio of 2 before entering the reforming reactor (8). The requested water is diverted from the steam cycle water supply, thus reducing the steam turbine flow rate (13). Part of the incoming energy is fed to the combustor (7) to deliver the required heat for the reforming process (8). For coherence in this proof, this fuel is assumed to be methane whereas in reality it has to be replaced by biomass. The amount of diverted fuel (e.g. biomass) is such that the biomass energy input into the cycle reaches 5%. The comburant air is taken from the turbine exhaust gas (6). Its flow rate is adjusted to yield 6% of excess oxygen in the combustor. The heat in the combustion tail gas is to be used as a heat source in the black box (9). The syngas is cooled down (10) to a temperature suitable for the nozzle and combustion chamber. According to the assumed reformer temperature, the syngas at exit of the reformer can be considered as in equilibrium : it contains 35.7% of hydrogen, 3.4% CO, 6.4% CO_2, 12% methane and 42.5% water (in mole fraction).

Table 1 summarises all the relevant boundary conditions of both systems, without and with reforming. Small differences are observed, due to the following

- Part of the fuel is diverted to a different route through the combustor and next to the stack, without being expanded in the turbine.
- Part of the water from the steam cycle is diverted to the reformer and gas turbine, lowering the flow rate of the steam turbine

The total water flow rate however, remains constant. When keeping the stack temperature constant and the HEN adiabatic, excess heat is found which must be rerouted inside the black box, where the sole appropriate heat sink is the syngas. The loss in mass flow and power in the steam turbine can thus be compensated by the increased mass flow through the main turbine and elevated methane and syngas injection temperatures.

A marginal LHV efficiency of the diverted fuel η^{mar} can be defined as follows

$$\eta^{mar} = \frac{\dot{W} - \eta^{ref}\dot{m}^{meth}LHV^{ref}}{\dot{m}^{bio}LHV^{bio}}\eta^{ref} = \frac{\dot{W}^{ref}}{\dot{m}^{ref}LHV^{ref}}. \tag{3}$$

In these formulas, $\dot{m}^{meth}$stands for the remaining methane mass flow in the adapted gas turbine cycle and $\dot{m}^{bio}$ stands for the diverted 'biomass' fuel. The reference LHV efficiency $\eta^{ref}$is determined for the original cycle in which all the energy input is methane. By means of η^{ref}, the remaining fossil fuel in the adapted cycle would provide a power output equal to $\eta^{ref}\dot{m}^{meth}LHV^{ref}$ and the surplus work can be attributed to the diverted methane (or biomass). The 'overall' efficiency in Table 2 corresponds to the conventional thermal cycle efficiency, defined as

$$\eta = \frac{\dot{W}}{\dot{m}^{meth}LHV^{meth} + \dot{m}^{bio}LHV^{bio}}. \tag{4}$$

As indicated in Table 2a, the adiabatic condition of the black box needs the combustor injection temperature to be forced up to 470 °C, delivering a marginal efficiency of over 60%. Although this may seem very interesting in theory, in practice such an injection temperature is too high. If the residual heat is allocated to the bottom cycle to produce more superheated steam instead of heating the syngas, a 20% drop in marginal efficiency is observed when

Table 2
Main results from the considered scenarios

Case	Reference	a	b	c	d
Main methane (g/s)	17.31	17.61	18.54	17.0	17.4
Diverted methane (biomass, g/s)	0	8.84	9.3	8.94	7.1
Net specific power (kW/kg)	436	447	458	442	439
Comb. injection temp. (°C)	150	470	150	150	350
Overall efficiency (%)	50.4	50.9	49.5	50.0	50.4
'Biomass' marginal efficiency	na	60.2	31.2	41.8	51.7

(a) 5% biomass, constant water flow, no condenser or saturation tower; (b) 5% biomass, constant comb. inj. temp., all heat assigned to the bottom cycle; (c) 5% biomass, constant comb. inj. temp., all heat assigned to; the bottom cycle, addition of a condenser; (d) 5% biomass, constant water flow, with condenser and saturation tower.

compared to the reference cycle (Table 2b). This can be explained as follows. The amount of water routed to the reformer corresponds to a 100% surplus of water to methane in the reactor. The excess water remains in the syngas and is injected into the combustion chamber further down the road. The excess water therefore behaves as a steam-injected gas turbine cycle, instead of the more efficient steam and gas Combined Cycle. A condenser is therefore needed to maintain the higher CC efficiency, to separate the excess water from the syngas and feed it to the bottom cycle.

5. Reforming cycle with condenser

When introducing a condenser in the BBHRS at a temperature of 50 °C into the adapted cycle, the major part of the 42.5% water (mol fraction) can be recuperated and routed to in the bottom cycle at 20 atm. This condensation raises the marginal efficiency by ten percent and compensates half of the loss found when no condenser was used (Table 2c). For the results shown in Table 2c, all the residual heat was used in the bottom cycle, resulting in an increase in water flow rate from 0.1323 in the reference case to 0.137 in the adapted case. For comparison purposes however, it is better to keep the water flow rate constant as it is a boundary condition of the black box. After preheating, evaporating and superheating a 0.1323 kg/s water flow rate to 350 °C, the remaining heat is used to increase the syngas injection temperature, making the box adiabatic. The resulting marginal efficiency surpasses the reference cycle efficiency and the injection temperature of 360 °C is more realistic for current injection nozzles (Table 2d).

Fig. 7 shows the corresponding composite curves. The composite curves show that hot and cold are in balance in the adapted cycle. A cross-pinch or second law violation however occurs at boiler inlet, rendering the BBHRS unfeasible. This problem can be solved by the more gradual evaporation within a saturation tower. This saturation tower mixes water and methane before entering the reforming reactor rather than evaporating water at a constant temperature in a conventional boiler.

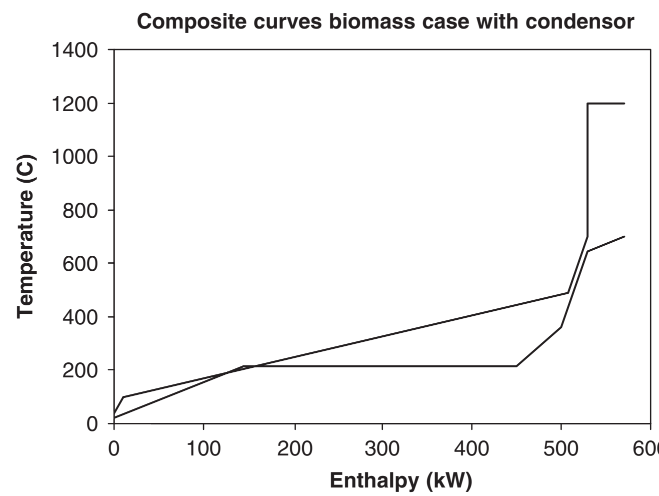

Fig. 7. Composite curves of the adapted case (5% energy from biomass, condenser included).

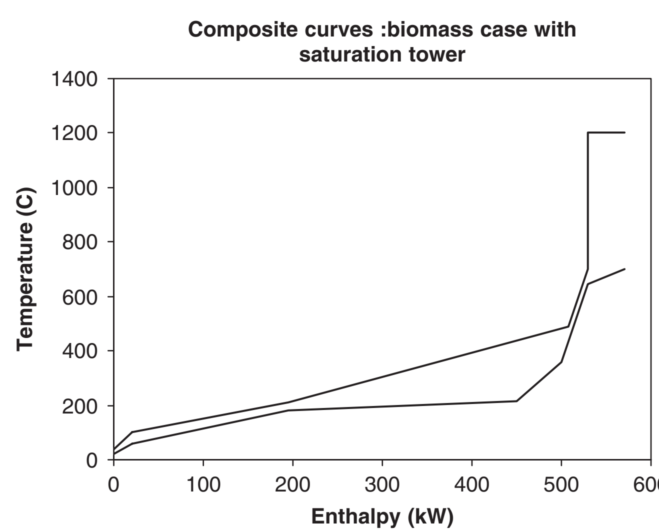

Fig. 8. Composite curves of the adapted case *with* the introduction of a saturation tower.

6. Reforming cycle with condenser and saturation tower

Fig. 9 shows a final and real arrangement of the HEN, with inclusion of a saturation tower. Methane and liquid

water are preheated and fed to the counter stream saturation tower, where water is evaporated at a variable temperature. In order to reach a steam–methane ratio of three, the inlet temperature of water and (to a lesser extent) methane must be sufficiently high so the desired amount of water is mixed into the methane. Before entering the reformer, the mixture is further preheated to 650 °C. Fig. 8 shows the corresponding composite curves. Both curves are kept on a comfortable temperature difference from each other, in contrast to the curves without saturation tower in Fig. 7. The inclusion of a saturation tower also reduces the quality requirements of the consumed water. Salts and sulfur tend to lag behind in the recirculating surplus of water, ruling out expensive purification systems [8].

Table 3
Boundary conditions of the reference case and base 5% energy from biomass case with saturation tower and condenser included

		Reference case	5% energy from biomass
Methane in	kg/s	0.017308	0.017402
Water in	kg/s	0.1323	0.1326
Steam Turbine In	kg/s	0.1323	0.1273
Stack out	kg/s	1.0173	1.0227

Tables 2d and 3 confirm that whilst keeping the boundary conditions (nearly) constant, the adapted cycle is capable of maintaining and even surpassing the reference cycle efficiency. The inherent loss in efficiency due to diversion of water and gas can be compensated by the increase in injection temperature of the syngas.

To conclude the simulation, pinch analysis can be applied to make the synthesis of the BBHRS as shown in Fig. 9.

7. Conclusions

The present paper demonstrates that it is possible to combine the advantages of external and internal firing of biomass without a significant drop in efficiency by means of (partial) steam reforming of natural gas. To achieve this performance, the adapted cycle has to satisfy three conditions :

- Excess heat in the stack must be compensated by raising the gas temperature at inlet of the gas turbine combustor.
- Excess water in the syngas must be condensed and routed to the bottom cycle

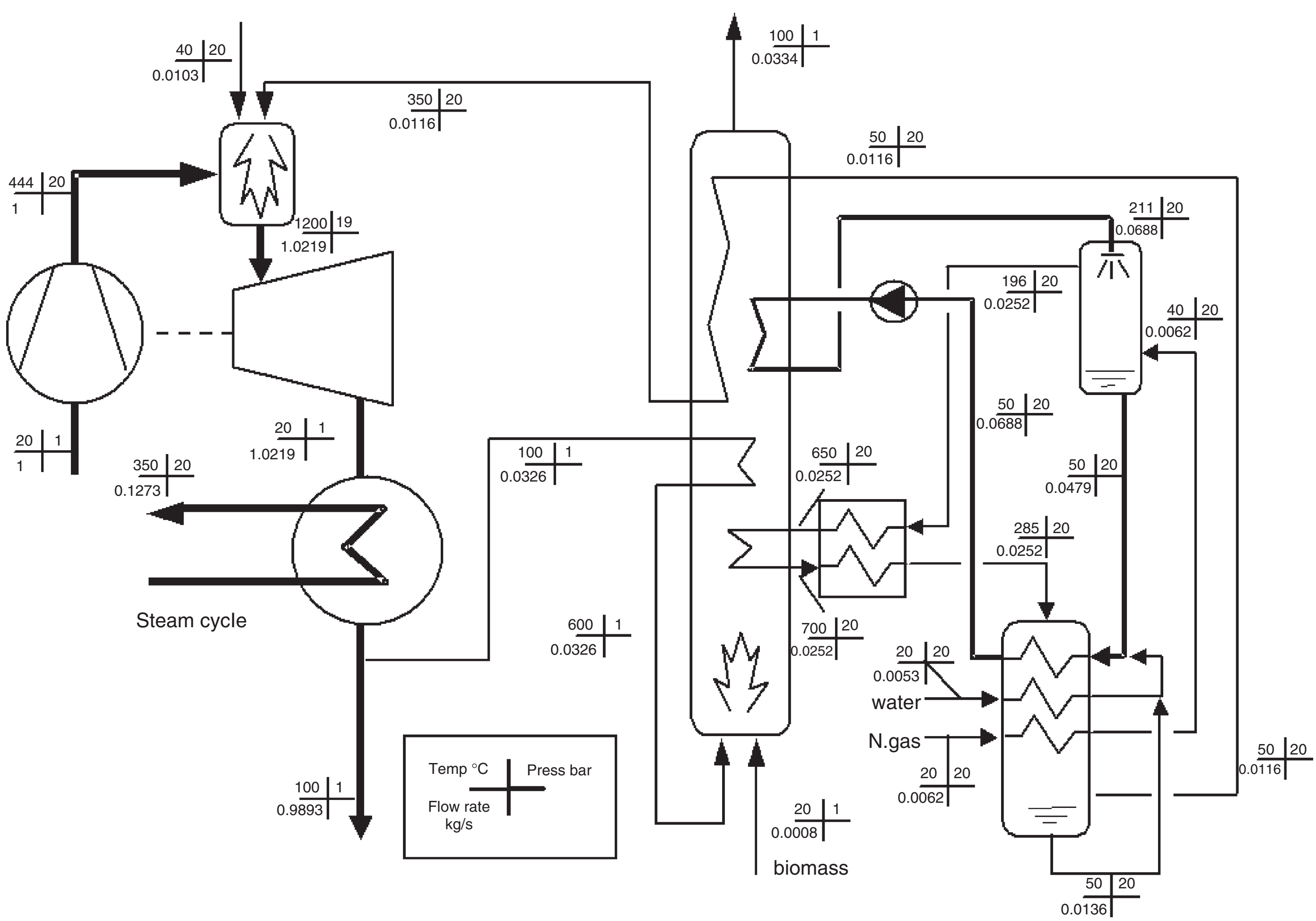

Fig. 9. Synthesis of the reforming case including condenser and saturation tower (5% energy from biomass).

- A saturation tower is necessary to avoid a second law violation when keeping the water flow constant

The suggested alternative route has minimal interference with the reference cycle and allows a biomass energy input of 5%, resulting in a cycle-efficiency, which is almost the same as the unmodified reference cycle. In the considered case, biomass is converted at a marginal efficiency of 51.7%, which is a very high conversion efficiency for an external combustion route. Such a high efficiency can be obtained if some stack heat is routed to the syngas, leading however to increased gas temperatures in the combustor nozzles. It is to be observed that the volume flow in the combustor nozzles is nearly doubled in the adapted case.

The next logical step will be the simulation of an existing power plant, with a comparison between the reference and the adapted cycle. This simulation will deliver the final theoretical proof of the capabilities of the suggested biomass process. If no significant drop in efficiency is noted for a 5% biomass energy input, this alternative route is worth to be tested in practice.

Acknowledgment

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